RF Signal Processing in Multi-Antenna Systems

Field of the Invention

[01]	The invention relates generally to multi-antenna communication systems, and more particularly to processing RF signals transmitted through spatially correlated channels in such systems.

Background of the Invention

[02]	Multi-antenna systems are widely considered to be the most viable way for significantly increasing the bandwidth efficiency of wireless data transmission systems. In MIMO (multiple input multiple output) systems, multiple antennas are deployed both at the transmitter and the receiver. In MISO (multiple input single output) systems, the receiver has only one antenna, and the multiple transmit antennas are used for transmit diversity. In SIMO (single input multiple output) systems, the transmitter has a single antenna, and multiple antennas are used at the receiver.

[03]	Given multiple antennas, the spatial dimension of the channel can be exploited to improve the performance of the wireless link. The performance is often measured as the average bit rate (bit/s) the wireless link can provide, or as the average bit error rate (BER), depending on the application.

[04]   Given a multi-antenna channel, a duplex method, and a transmission bandwidth, the multiple-antenna system can be categorized as narrowband or wideband (i.e., the channel is flat or frequency selective fading within the system bandwidth), and possessing either full, partial or no channel state information (CSI).

[05]   Multiple antennas provide enhanced performance. Studies show that the multiple antennas can be used to provide spatial diversity, and/or can increase the information-theoretic capacity (data rate), see, e.g., Vaughn and Anderson, *Channels, propagation, and antennas for mobile communications*, IEE Press, 2003, Telatar et al., "Capacity of Multi-Antenna Gaussian Channels," *European Trans. on Telecomm.*, Vol. 10, No. 6, pp. 585-596, November-December 1999, Winters, "On the Capacity of Radio Communication Systems with Diversity in Rayleigh Fading Environments," *IEEE J. Selected Areas Comm.*, 1987, and Tarokh et al., "Space-Time Codes for High Data Rate Wireless Communication: Performance Criterion and Code Construction," *IEEE Trans. Inform. Theory*, Vol. 44, pp. 744-765, March 1999.

[06]   However, as a disadvantage, operation with multiple RF chains increases complexity and cost. An antenna selection technique can be used to determine an optimal subset of antennas. This still yields improved performance while reducing the number of required RF chains, see Molisch et al., "Capacity of MIMO Systems with Antenna Selection," *Proc. IEEE Intl. Comm. Conf.*, pp. 570-574, 2001, and Gore et al., "MIMO Antenna

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Subset Selection with Space-Time Coding," *IEEE Trans. Signal Processing*, Vol. 50, No. 10, pp. 2580-2588, October 2002.

[07]   Most prior art antenna selection techniques have focused only on selecting a subset of antennas before down-conversion and processing in baseband. This (spatial) antenna selection techniques work reasonably well under some circumstances, namely in the case that (i) the number of selected antennas is only slightly smaller than the number of available elements, and (ii) the MIMO channel is spatially uncorrelated.

[08]   However, in reality, correlated scattering at both the transmitter and receiver antenna arrays is more usual. Due to the directional transmission in the wireless environment, the signal waveforms can be highly correlated depending on the departure and arriving angles at the antennas.

[09]   The prior art antenna selection techniques that operate only in the spatial domain can have a significant degradation in performance when dealing with this correlation. Furthermore, even for weak correlations, the prior art antennas also show a significant performance loss when the number of selected antennas is considerably smaller than the number of available antennas.

[010]   Therefore, it is desired to provide an RF signal processing technique that overcomes the problems of the prior art.

Summary of the Invention

[011]   The invention provides a system and method for antenna subset selection in a multi-antenna communication system based on the joint signal processing in radio frequency and baseband. The system is designed for either full diversity transmission or multiplexing transmission, in both correlated and uncorrelated channels.

[012]   The invention uses phase-shift operations in radio-frequency (RF) chains. The operations can be performed after antenna selection in the transmitter, or before antenna selection in the receiver, or both.

Brief Description of the Drawings

[013]   Figure 1 is a block diagram of a multi-antenna system that uses joint RF/baseband signal processing for antenna selection according to the invention; and

[014]   Figures 2 and 3 are graphs comparing RF signal processing techniques.

Detailed Description of the Preferred Embodiment

[015]   Figure 1 shows a multi-antenna system 100 that uses the antenna selection method according to the invention. In a transmitter 1, L_t data streams 101 are generated. These streams can be either different signals

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obtained through a space-time coder, i.e., in multiplexing transmission, or the same signal encoded with different weights, i.e., in diversity transmission. The streams are modulated 110 to passband RF signals. A selection switch 120 links these signals to L_t of the t branches 121 associated with the t transmit antennas ($t \geq L_t$). In the new invention, the t passband branches 121 are transformed 130 by a $t \times t$ matrix operation Φ_1 before they are applied to the t transmit antennas, and passed through the channel 140.

[016]   At a receiver 2, the signals are received via the channel 140 by r antennas. The received signals are transformed 150 by an $r \times r$ matrix operation Φ_2, and L_r of the transformed signals are selected 160, where $L_r \leq r$. The selected signals 161 are demodulated 170 and further processed 180 in baseband for detection of the data streams 101. The concatenation of the L_t out of t switch and the $t \times t$ matrix operation Φ_1 can be viewed, and implemented, as a $t \times L_t$ matrix operation in both the transmitter and the receiver.

[017]   In order to reduce the implementation cost in radio frequency, the entries of the matrix operations usually are constrained to be pure phase shifters without power amplifiers. They can also be done just in the transmitter, or just in the receiver, e.g., by making the corresponding matrix at the other link end, Φ_2 or Φ_1, identity matrices.

[018] System and Channel Model

[019] For the description of the operating principles of the invention, we use a well known channel model, see Shiu et al., "Fading Correlation and Its Effect on the Capacity of Multi-element Antenna Systems," *IEEE Trans. Commun.*, Col. 48, pp. 502-513, March 2000, Bölcskei et al., "Performance Analysis of Space-Time Codes in Correlated Rayleigh Fading Environments," *Proc. Asilomar Conf. Signals, Syst. Comput.*, pp. 687-693, November 2000, Gore et al., "MIMO Antenna Subset Selection with Space-Time Coding," *IEEE Trans. Signal Processing*, Vol. 50, No. 10, pp. 2580-2588, October 2002. However, we note that the invention is in no way dependent on the channel model.

[020] The model for the channel transfer function $\mathbf{H}$ is expressed as:
$$\mathbf{H} = \mathbf{R}^{1/2}\mathbf{W}\mathbf{T}^{1/2}, \tag{1}$$
where $\mathbf{W}$ is a Rayleigh fading matrix with i.i.d. complex Gaussian entries $\sim N_C(0,1)$. The correlation matrices $\mathbf{R}$ and $\mathbf{T}$ denote receive and transmit correlations, respectively. The sizes of $\mathbf{R}$ and $\mathbf{T}$ are $r \times r$ and $t \times t$, respectively. This model is usually valid when assuming independent transmit and receive correlations.

[021] To facilitate the performance analysis, we introduce the singular value decomposition (SVD) of the transfer function matrix $\mathbf{H}$: $\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^*$, where $\mathbf{U}$ and $\mathbf{V}$ are unitary matrices representing the left and right singular vector spaces of $\mathbf{H}$, respectively; and $\mathbf{\Sigma}$ is the diagonal matrix consisting of all the singular values of H. For convenience we denote $\lambda_i(\mathbf{H})$ as the i-th

largest singular value of matrix $\mathbf{H}$, and $\vec{u}_i(\mathbf{H})$, $\vec{v}_i(\mathbf{H})$ are the left and right singular vectors of $\mathbf{H}$ with respect to $\lambda_i(\mathbf{H})$. Here we use '*' to denote the conjugate transpose of a vector or matrix (It reduces to the complex conjugate for a scalar).

[022]   Diversity Transmission

[023]   Full-Complexity (FC) MRT/MRC Scheme

[024]   The system 100 with diversity transmission can be expressed by a linear equation 1.

$$\vec{x}(k) = \mathbf{H}\vec{v}s(k) + \vec{n}(k),$$ (3)

where $s(k) \in C$ is the transmitting stream, $\vec{x}(k) \in C^r$ is the set of sample stacks of the complex-valued receiver data sequence. The total transmission power is constrained to P. The thermal noise $\vec{n}(k) \in C^r$ is a white i.i.d Gaussian random process with independent real and imaginary parts and variance $\sigma_n^2 I_r$, and $\vec{V}$ is a t-dimensional transmitter weighting vector satisfying $\|\vec{V}\| = 1$. At the receiver, the received signals $\vec{x}$ are weighted with complex weights $\vec{u}^*$ and added, to give a soft estimate of the transmitted symbol stream.

[025]   Without antenna selection, the information stream $s(k)$ is estimated by performing a linear combination of all the r observation streams with a coefficient vector $\vec{u}^*$ at the receiver by:

$$\hat{s}(k) = \vec{u}^*\mathbf{H}\vec{v}s(k) + \vec{u}^*\vec{n}(k).$$ (4)

The estimate SNR after combining is

a.
$$\frac{\mathcal{E}[|\vec{u}^{*}\mathbf{H}\vec{v}s(k)]|^{2}}{|\vec{u}^{*}\vec{n}(k)|^{2}} = \rho\frac{|\vec{u}^{*}\mathbf{H}\vec{v}|^{2}}{|\vec{u}^{*}|^{2}},$$

(5)

where the nominal SNR is $\rho = P/\sigma_{n}^{2}$. To maximize the estimate SNR,

maximal ratio transmission and maximal ratio combining are used, i.e.,

$\vec{u}(\vec{v})$ are the singular vectors in $\mathbf{U}$ ($\mathbf{V}$) corresponding to the largest singular

value $\lambda_{1}(\mathbf{H})$. The resulting estimated SNR is then $\rho\lambda_{1}^{2}(\mathbf{H})$.

[026]   **Conventional Hybrid Selection (HS) MRT/MRC Method**

[027]   When L_{r} out of the r receive antennas are selected and combined,

each selection option corresponds to a $L_{r} \times r$ selection matrix on the transfer

function, which extracts L_{r} out of the r rows of the matrix $\mathbf{H}$ that are

associated with the selected antennas. We denote S_{r} as the set of all such

selection matrices. Similarly, an L_{t} out of t selection in the transmit end can

be represented by a $t \times L_{t}$ matrix, and the set of the transmit selection

matrices are denoted by S_{t}. For any selection option ($S_{1}\in S_{t}, S_{2}\in S_{r}$), an

optimal SNR is achieved via a similar MRT and MRC on the L_{t} transmit and

L_{r} receive branches respectively:

$$\max_{\vec{u}\in C^{L_{r}}} \max_{\|\vec{v}\|=1} \rho\frac{\|\vec{u}^{*}\mathbf{S}_{2}\mathbf{H}\mathbf{S}_{1}\vec{v}\|^{2}}{\|\vec{u}\|^{2}} = \rho\lambda_{1}^{2}(\mathbf{S}_{2}\mathbf{H}\mathbf{S}_{1}).$$

(7)

The HS-MRC scheme selects the optimal antenna subset selection matrices

(S_{1}, S_{2}) among all the elements in S_{t} and S_{r} that maximize the estimate SNR

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above:
$$SNR_{HS} = \max_{S_2 \in S_r} \max_{S_1 \in S_t} \rho \lambda_1^2 (\mathbf{S_2 H S_1}).$$

(8)

[028]   **FFT-Based Method (FFTS)**

[029]   To cope with the highly correlated MIMO channels, the operation

($\mathbf{\Phi_t}$ or $\mathbf{\Phi_r}$) 150 can be a fast Fourier transform matrix of the form:

$$\mathbf{\Phi_r} = \frac{1}{\sqrt{r}} \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 1 & e^{-j\omega_r} & \cdots & e^{-j(r-1)\omega_r} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & e^{-j(r-1)\omega_r} & \cdots & e^{-j(r-1)^2\omega_r} \end{bmatrix},$$

i.

where $W_r = 2\pi/r$. The matrix is normalized to preserve the noise level. Via a

similar MRT/MRC on the selected branches after the FFT, the optimal

estimate SNR is:

$$SNR_{FFTS} = \max_{S_2 \in S_r} \max_{S_1 \in S_t} \rho \lambda_1^2 (\mathbf{S_2 \Phi_r H \Phi_t S_1}). \qquad (9)$$

[030]   **Phase-Shift & Selection Method (PSS)**

[031]   A more general design in our invention is to allow phase-shift-

only entries in the transform $\mathbf{\Phi_1}$ 130 (and/or $\mathbf{\Phi_2}$ 150). In this case, the

transform matrix 130 (150) and the selection 120 (160) can be integrated

into one $t \times L_t$ (or $L_r \times r$) matrix with phase-shift-only entries. The set of all

such transmit (or receive) matrices is denoted by F_t (or F_r). In this method,

with the two phase-shift matrices $\mathbf{F_1} \in F_t$ and $\mathbf{F_2} \in F_r$, the linear combining is

performed on the virtual channel $\mathbf{F_2 H F_1}$. As above, the SNR for the optimal

choice of $(\mathbf{F_1}, \mathbf{F_2})$ is $\quad SNR_{PSS} = \max_{\vec{u} \in C^{L_r}} \max_{\vec{v} \in C^{L_t}} \max_{\mathbf{F_1} \in F_t} \max_{\mathbf{F_2} \in F_r} \rho \dfrac{\| \vec{u}^* \mathbf{F_2} \mathbf{H} \mathbf{F_1} \vec{v} \|^2}{\| \vec{u}^* \mathbf{F_2} \|^2 \| \mathbf{F_1} \vec{v} \|^2}.$

(10)

When $L_r \geq 2$ and $L_t \geq 2$, the optimal solution for equation (10) can be derived in a closed form. Denote the elements in $\mathbf{F_2}$ as $[\mathbf{F_2}]_{m,n} = \exp(j\phi_{m,n})$ and the singular vector of $\mathbf{H}$ as $\vec{u}_1^*(\mathbf{H}) = \begin{bmatrix} \beta_{11} e^{-j\varphi_{11}} & \cdots & \beta_{r1} e^{-j\varphi_{r1}} \end{bmatrix}$, an optimum choice of the phases in $\mathbf{F_2}$ is

$$\phi_{1,i} = -\varphi_{i,1} - \cos^{-1} \frac{\beta_{i,1}^2 + \beta_{max}\beta_{min}}{\beta_{i,1}(\beta_{max} + \beta_{min})};$$

i. $\qquad \phi_{2,i} = -\varphi_{i,1} + \cos^{-1} \frac{\beta_{i,1}^2 - \beta_{max}\beta_{min}}{\beta_{i,1}(\beta_{max} - \beta_{min})}.$

(11)

where $\beta_{max} = \max\limits_{1 \leq i \leq r} \beta_{i1}$ and $\beta_{min} = \min\limits_{1 \leq i \leq r} \beta_{i1}$. The other rows of $\mathbf{F_2}$ can be arbitrarily designed. The optimum phase shifters in $\mathbf{F_1}$ are derived in a similar fashion with $\vec{u}_1^*(\mathbf{H})$ replaced by $\vec{v}_1^*(\mathbf{H})$. With this choice, the PSS can achieve the same SNR as the FC-MRT/MRC.

[032]   When either $L_r = 1$ or $L_t = 1$ (or both), a closed-form solution to (10) in generally does not exist; we provide a sub-optimal solution which closely approximates the maximization in (10):

$$\phi_{1i} = -\varphi_{r1}. \qquad\qquad (12)$$

[033]   **Multiplexing Transmission**

[034]   **Full-Complexity (FC) Scheme**

[035]   The system 100 with multiplexing transmission is expressed by

$$\vec{x}(k) = \mathbf{H}\,\vec{s}(k) + \vec{n}(k) ,\qquad\qquad (13)$$

where $s(k) \in C^t$ is now a t-dimensional vector denoting the different

transmitting sequences. The assumptions on the channel and noise are the

same as the diversity transmission case. To support multiple data streams,

capacity is an important measure for the capacity of the system.

[036]   Without antenna selection, the information rate supported by the

original channel can be maximized using a "water-filling" power allocation.

The capacity of the original system is

$$C_{FC} = \sum_{i=1}^{\min(t,r)} [\log_2 \frac{\rho}{t}\mu\lambda_i^2(\mathbf{H})]^+ , \qquad\qquad (14)$$

where $[a]^+$ is defined as max(a,0 and μ is the constant satisfying

$$\sum_{i=1}^{\min(t,r)} [\mu - \frac{t}{\rho\lambda_i^2(\mathbf{H})}]^+ = t .$$

[037]   **Conventional Hybrid Selection (HS) Method**

[038]   When L_t (L_r) out of the t (r) transmit (receive) antennas are

selected, the maximum capacity offered by the conventional antenna

selection scheme is

$$C_{HS} = \max_{S_1 \in S_t} \max_{S_2 \in S_r} \sum_{i=1}^{\kappa(S_2\mathbf{HS}_1)} [\log_2 \frac{\rho}{t}\mu\lambda_i^2(S_2\mathbf{HS}_1)]^+ ,$$

(15)

where μ depends on $(\mathbf{S_1}, \mathbf{S_2})$ and satisfies $\displaystyle\sum_{i=1}^{\min(L_t, L_r)} [\mu - \frac{t}{\rho \lambda_i^2 (\mathbf{S_2 H S_1})}]^+ = t$.

[039]   FFT-based Method (FFTS)

[040]   Similar to the FFTS in diversity transmission case, the FFT matrix is inserted in the RF chains together with the selection switch. The optimum selection with FFT can deliver a capacity of

$$C_{FFTS} = \max_{\mathbf{S_1} \in S_t} \max_{\mathbf{S_2} \in S_r} \sum_{i=1}^{\min(L_t, L_r)} [\log_2 \frac{\rho}{t} \mu \lambda_i^2 (\mathbf{S_2 \Phi_r H \Phi_t S_1})]^+ ,$$

(16)

with the constraint $\displaystyle\sum_{i=1}^{\min(L_t, L_r)} [\mu - \frac{t}{\rho \lambda_i^2 (\mathbf{S_2 \Phi_r H \Phi_t S_1})}]^+ = t$.

[041]   Phase-Shift & Selection Method (PSS)

[042]   For PSS method, we use the same notations as before

$$C_{PSS} = \max_{\mathbf{F_1} \in F_t} \max_{\mathbf{F_2} \in F_r} \sum_{i=1}^{L} [\log_2 \frac{\rho}{t} \mu \lambda_i^2 (\mathbf{F_2 H F_1})]^+$$

[043]   Partial CSI

[044]   In the case that the channel is only partially estimated, the invention provides an alternative method. In this case, there is no knowledge about the instantaneous channel state, but rather only about the state of the channel averaged over a time interval, e.g., typically, but not

restricted to, several milliseconds to several hundreds of milliseconds. This case typically occurs for the transmitter in a frequency-division duplexing system,

[045]   In that case, the goal of the transformation is to transform the transmit signal in such a way that *on average* the signals after the selection process has good properties, e.g., high capacity.

[046]   The expected value capacity that can be achieved that way is

$$E\{C_{PSS}\} = \max_{\mathbf{F_1} \in F_t} \max_{\mathbf{F_2} \in F_r} E\{\sum_{i=1}^{L} [\log_2 \frac{\rho}{t} \mu \lambda_i^2 (\mathbf{F_2 H F_1})]^+\}.$$

The expected value of the capacity is only one possible criterion. Other criteria result in different values for the capacity matrix.

[047]   Effect of the Invention

[048]   Figure 2 compares the SNR gain of the four methods described above as a function of antenna spacing with diversity transmission. The parameters in the system are $t=8$, $r=8$, $L_t=1$, $L_r=2$. For large correlation, i.e., small antenna spacing, the FFTS method in the invention has a considerably larger SNR gain over the traditional HS-MRT/MRC method. In general, regardless of the correlation level in the channel, the PPS method in the invention can outperform both prior art selection methods. In fact with two or more RF branches, the PSS method can achieve the SNR gain of a full-complexity method.

[049] Figure 3 displays the 5% outage capacity of the four methods for multiplexing transmission. The system parameters are $t=3$, $r=8$, $L_t=3$, $L_r=3$, $\rho=20$ db. A similar conclusion can be drawn from the plots: the FFTS shows a performance improvement for strongly correlated channels while the PPS works well for both strong and weak correlations.

[050] This invention is described using specific terms and examples. It is to be understood that various other adaptations and modifications may be made within the spirit and scope of the invention. Therefore, it is the object of the appended claims to cover all such variations and modifications as come within the true spirit and scope of the invention.